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HINS_CH_SOL_03d-1 Fabrication Summary and Test Results

G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, T. Wokas

I. Fabrication Summary

The original prototype type 2 solenoid, HINS_CH_SOL_03d, was first tested in June 2007 [1]. At that time quenches in one of the bucking coils (BC) appeared to be limiting the quench performance (after it had reached significantly higher current levels). Therefore the test was ended and the decision made to disassemble and dissect the limiting coil, BC08, to determine if there were flaws during the fabrication. In fact, the coil was found to be "perfect", and the working hypothesis is now that the reduction in quench current may have been a thermal effect (see also [2] and [3]). Subsequently, the solenoid was reconstructed using two newly wound bucking coils, BC13 and BC14, but with the original main coil (P04) and corrector dipole coils (V02, H02) which had been epoxy impregnated together. The new bucking coils were wound from the same reel of Oxford 0.6 mm NbTi strand used to fabricate HINS_CH_SOL_05 (Oxford billet 8538-1B, reel 1797A1), with properties tabulated in [2]; the remainder of this spool has been shipped to Cryomagnetics, Inc. for use in the production of CH solenoid bucking coils. The BC strand critical parameters, and all final dimensions (including number of turns in windings) for the assembled coils are identical to those of the original solenoid, so that magnetic field distributions and quench properties are expected to be the same as for the original; the rebuilt solenoid is designated HINS_CH_SOL_03d-1.

II. Test Overview

The solenoid was mounted in the stand 3 assembly and carefully inspected prior to installation and electrical checkout, following lessons learned from the test of HINS_CH_SOL_05 [3]. All three pairs of power leads were utilized to separately power a) the main coil (MC), b) the two bucking coils (BC) already spliced in series, and c) the horizontal and vertical corrector dipoles (CD) already spliced in series. Warm magnetic measurement profiles of each circuit were taken at 0.5A on 12/12/07 and checked for polarity. The cool down to 4.2 K was made on 12/13/07, and cold testing was completed on 12/14/07 with a total consumption of about 2.5 500 liter helium dewars. The cool down was faster than it was in the previous tests, perhaps because the stand 3 test dewar vent was a couple of inches higher than in the past, which may have cooled the stand more efficiently. However, other problems caused a long delay to powering the solenoid: the most time consuming problems resulted from interface box electronics and Lakeshore power supply failures, similar to what had been encountered previously during the HINS_CH_SOL_04d test. The cold hipot of the BC leads "failed" (>12 μA current at 500V), but later passed after cleaning and drying the leads. The helium transfer line developed a blockage after the cold valve was closed to conserve helium while debugging electronics; this was bypassed and manually controlled for much of the remaining time. Quench training began late on 12/13/07, then resumed and was completed early on 12/14/07. A series of magnetic measurements were then taken, and the test ended with quenches at higher ramp rates.

III. Quench Performance

The dump resistor was installed across the MC+BC for the entire test (except during PS debugging), and the bus connections were made as shown in Fig. 1; (this differed slightly from the desired connection scheme that was designed to reduce internal voltages). The early quench events were somewhat difficult to interpret, because we began with a 1V detection threshold that did not allow much voltage development above the offset caused by ramping: U0 = L·dI/dt. Some adjustments to QC process variable labels were then made after the first four ramps, to remove old/unused channels and clarify some signal names. Also, after electronics repairs - for reasons unclear to the users - a scale factor of 4/3 appeared between the requested and the actual target current and ramp rate: thus, training ramp rates were actually at 1.3 A/s instead of 1 A/s.

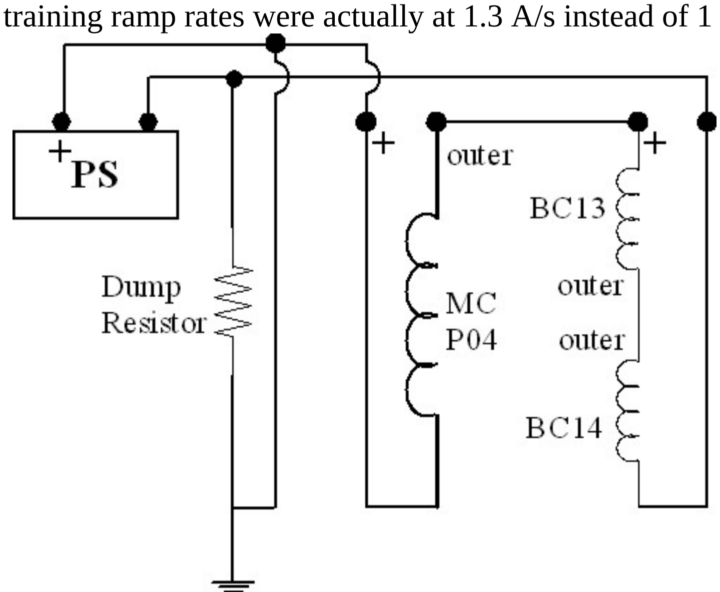

Fig. 1. PS connection scheme for this test; leads from outer coil windings are labeled.

The expected quench current was 233A at 4.2K, as in [1], and the bath temperature during quench tests varied between 4.20 and 4.29K. The ramp and quench history is shown in Fig. 2. The first five ramps were performed on 12/13/07, and the rest on 12/14/07. A minimum interval of 10 minutes was maintained between quenches to allow coil cooling.

During ramp 4 the detection system tripped at a low current (153A) and voltage signals are not consistent with expectations for a quench in any coil: the trip was detected by “half coil difference > 1V”, which was in fact the difference between bucking coils at this threshold (a remnant feature from the HTS Leads tests conducted previously). The BC13 (“+1/2BC”) signal grows to the -1V level in 8ms, and the MC voltage grows negative to about -0.6V. Following considerable checking of polarities (from warm system checkout data), we concluded that a real quench should result in positive voltage. One plausible scenario was suggested after inspection of the assembly after the test: cable ties securing the leads and voltage taps around the solenoid had broken, and rather large area loops between superconducting lead wires existed; so if a tie broke while ramping, that could have allowed rapid motion of the loop through the solenoid fringe field to generate a voltage. A 25 cm^2 loop moving for 5 ms through a 1T field would generate 0.5V – however, a fringe field this large seems somewhat unlikely, so quantitatively this scenario is marginal. The shapes of the signals suggest (rather fast) quench development, but the polarities are not understood.

The solenoid reached its expected maximum quench current after 11 ramps (233.6A) and repeated in ramp 12 (234 A). Ramp 13 was held at 200 A while corrector dipoles were powered in series to 275 A without a quench; the ramp subsequently was allowed to continue with correctors off (labeled 14). The quench current was slightly lower in this case (232.2 A), so one additional ramp to quench was made and it was somewhat lower still (227.8 A) for unknown reasons (temperature was 4.25K, liquid level was a little low – 10 cm above the magnet top and falling, but still above the magnet). Following magnetic measurements, two additional ramps were made at 2.67 A/s and 4 A/s – some slight increase in the actual quench current appeared in the last ramp (240.5 A at 4 A/s).

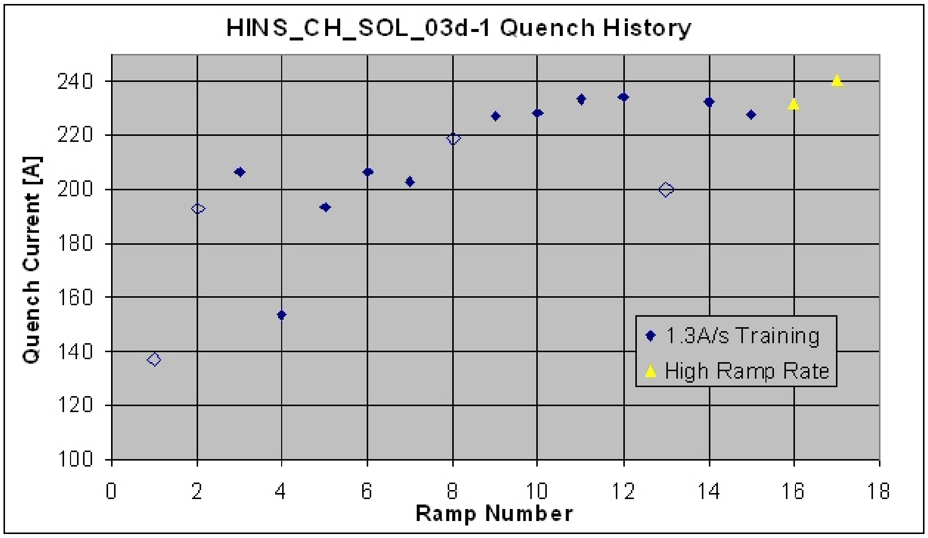

Fig. 2. Ramp and quench history for solenoid 03d-1 (note suppressed zero on vertical scale). Open symbols represent current levels reached without quenching.

IV. Magnetic Performance

Magnetic measurements were performed using the "new" 3D Hall Probe (serial number 54-06) with the standard Keithley multiplexing DMM for digitization, as in [3]. The probe orientation on the holder is shown in Fig. 3. In this test the probe was placed 12mm radially off-axis, in order to measure the level of non-uniformity in corrector dipole fields. Fig. 4 shows the radial and azimuthal field strength of the solenoid along its axis and a comparison of the measured ratio (peak B_z / peak B_x) versus radius with the Opera model prediction, which agrees with the probe radial position of 12mm. The model calculation, made at 130A, assumed as-built parameters (no iron gap), with default non-linear soft iron BH material properties. Fig. 5 shows agreement with the measured transfer function profile at this current, and Fig. 6 shows the current dependence due to saturation of the flux return material. The saturation effects in the fringe field region are illustrated in Fig. 7, where again the prediction is in very good agreement with the measured transfer functions. Finally, Fig. 8 shows the large variation in corrector dipole field strength as a function of angle, with both dipoles powered at 250 A, at a radius of 12 mm.

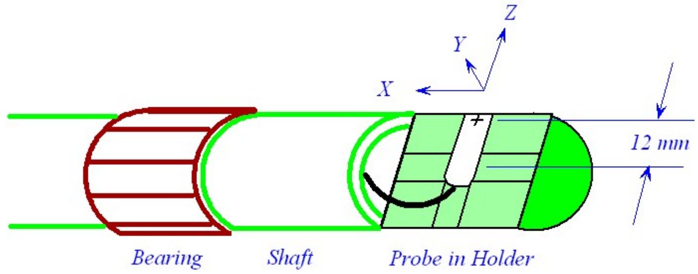

Fig. 3. 3D Hall Probe and coordinate orientations when mounted in off-axis position.

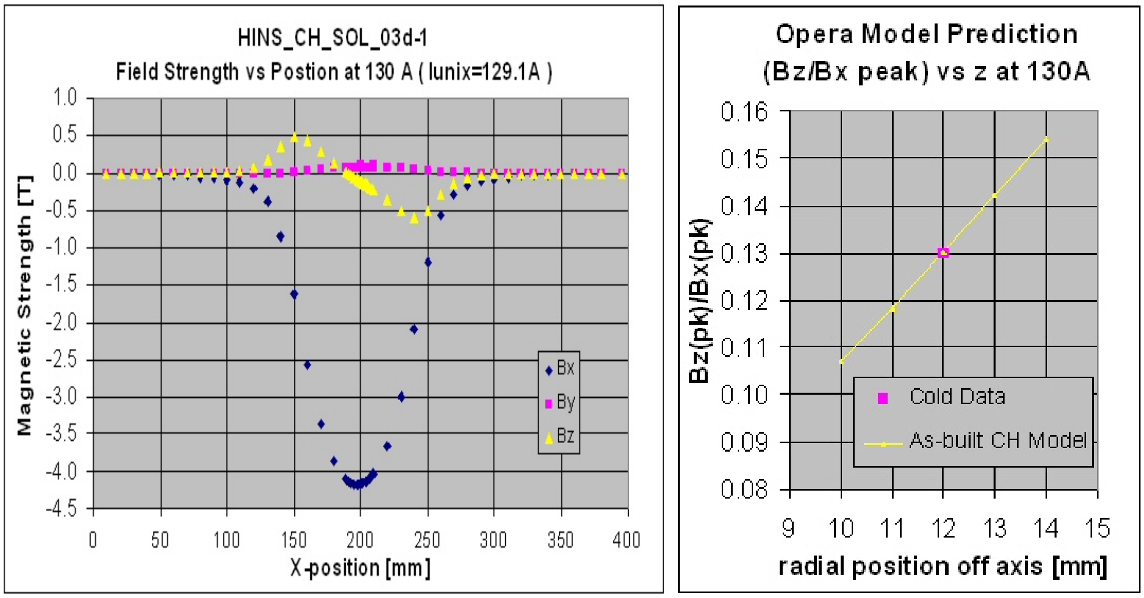

Fig. 4. Profiles of magnetic field strength along the solenoid axis (B_x) and radially outward (B_z), measured at a radius of 12mm from the solenoid axis. B_y measures tangential to the radial (that is azimuthal) direction and should be zero everywhere, so the B_y signal indicates a slight probe tilt. Model prediction (right) agrees well on the expected ratio (peak B_z/peak $B_{x)}$ vs radius.

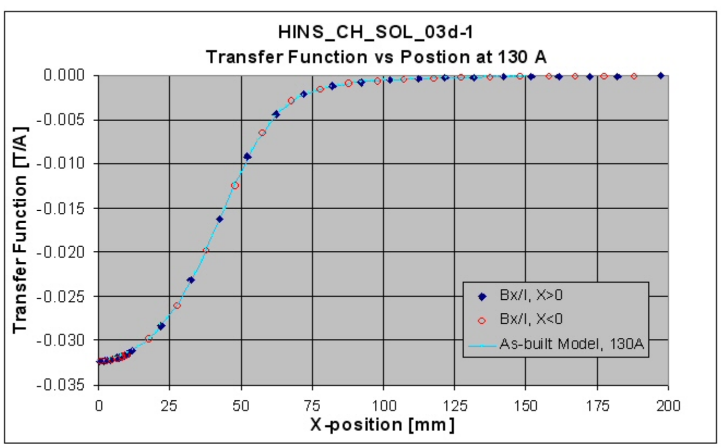

Fig. 5. Transfer function at 130A versus position (reflected about the center) measured and calculated with a 12 mm radial offset. The figure illustrates the symmetry and good agreement with model prediction.

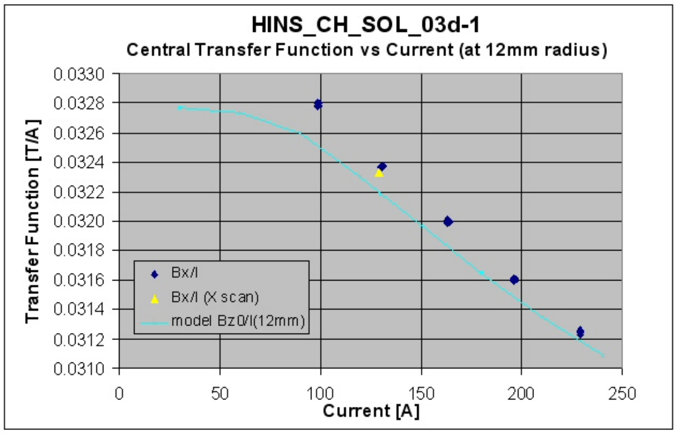

Fig.6. Transfer function (absolute value) at the solenoid center as a function of current, showing decline due to iron saturation at high field. The Opera model results are overlaid for comparison, and show very good agreement. The nominal operating current is 180 A.

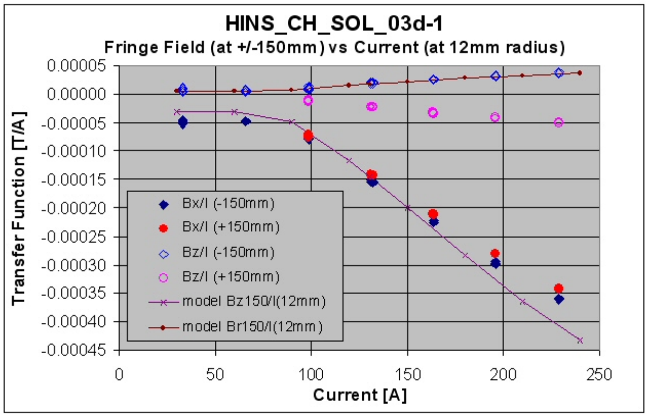

Fig. 7. Transfer function dependence on current in fringe field at 150 mm from solenoid center (at 12mm radial offset); radial (B_z) and axial (B_x) components are shown for data on both sides of the solenoid, and agreement with the model prediction is very good.

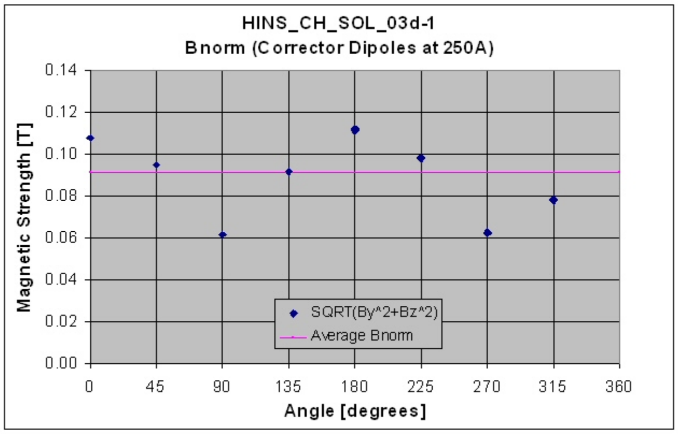

Fig. 8. Magnitude of dipole field strength for both horizontal and vertical dipole correctors powered in series at 250 A, as a function of probe angle with the probe offset radially 12 mm from the solenoid axis. The standard deviation is about 20 %.

V. Conclusions

The solenoid HINS_CH_SOL_03d-1 was rebuilt using the original main coil and corrector dipole coils with two new bucking coils, after one of the original bucking coils appeared to exhibit degraded quench performance after training. The rebuilt solenoid readily trained to the expected current level (233 A) and exhibited a training plateau with quench current variation of a few Amperes. Ramp rate dependence was explored up to 4 A/s, and the quench current was about the same, even slightly higher than expected at 4 A/s (240.5 A). Corrector dipoles were both powered to 275 A without quenching in the solenoid field at 200 A.

Magnetic measurements were made off-axis, primarily to confirm the prediction that this dipole corrector design results in inadequate field quality at large radius. In fact, the dipole field variation was found to be about 20% (RMS) at a radius of 12 mm from the solenoid axis. This is a result of a design flaw that had been identified some time ago and resulted in a redesign of the corrector. Solenoid vendor has been provided with the updated design drawings.

Measurements of the field profile agree very well with the predicted transfer function and shape, to better than 1% using the as-built model. Measurements of the field strength at the center and in the fringe regions as a function of current show the effects of iron saturation, which are also in very good agreement with the as-built model predictions.

Errata

A number of minor errors have been identified in previous test reports: in Figure 11 of [1] the vertical axis label is incorrect: the correct label should be “B [G]”, not “B/I [G/A]; the 3D magnetic measurement probe used for HINS_CH_SOL_04d measurements in [2] was actually the “3D new” probe “D”, not the “3D old” probe “C”; there are two tables labeled “Table 1” in [5]: the second one in section III should be “Table 3”.

References

1. E. Barzi, G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, D. Turrioni, T. Wokas, “Expected Performance and Test Resulst of the First Pre-Production Solenoid (Type 2, with Correctors): HINS_CH_SOL_03d”, FNAL, TD-07-021, August 2007.
2. E. Barzi, G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, D. Turrioni, T. Wokas, “HINS_CH_SOL_04d Expected Performance and Test Results”, FNAL, TD-07-027, October 20, 2007.
3. E. Barzi, G. Davis, C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, D. Turrioni, T. Wokas, “HINS_CH_SOL_05 Fabrication Summary and Test Results”, FNAL, TD-07-031, December 2007.
4. C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, T. Wokas, “Focusing Solenoid HINS_CH_SOL_01 Fabrication Notes and Test Results”, FNAL, TD-07-006, May 04, 2007.
5. C. Hess, F. Lewis, D. Orris, M. Tartaglia, I. Terechkine, T. Wokas, “Focusing Solenoid HINS_CH_SOL_02 Fabrication Notes and Test Results”, FNAL, TD-07-008, May 09, 2007.